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Determining the likelihood of pauses and surges in global warming

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Abstract

The recent warming 'hiatus' is subject to intense interest, with proposed causes including natural forcing and internal variability. Here, we derive samples of all natural and internal variability from observations and a recent proxy reconstruction to investigate the likelihood that these two sources of variability could produce a hiatus or rapid warming in surface temperature. The likelihood is found to be consistent with that calculated previously for models and exhibits a similar spatial pattern, with an Interdecadal Pacific Oscillation-like structure, although with more signal in the Atlantic than in model patterns. The number and length of events increases if natural forcing is also considered, particularly in the models. From the reconstruction it can be seen that large eruptions, such as Mount Tambora in 1815, or clusters of eruptions, may result in a hiatus of over 20 years, a finding supported by model results.

Introduction

The latest generation of climate models (Climate Model Intercomparison Project 5 - CMIP5; Taylor et al., 2012) predict current warming trends of global surface air temperature of approximately 0.2K per decade, much greater than the observed warming during the first part of this century (1998-2013; see e.g., Flato et al., 2013, Easterling and Wehner, 2009, Fyfe et al., 2013). In contrast, the warming over the recent five decades is similar between models and observations. The recent 'hiatus' period has received considerable attention (e.g., Hawkins et al., 2014). While limited coverage of the rapidly warming Arctic may have missed some of the observed global warming (Cowtan and Way, 2013), it does not explain the recent model-data mismatch because most analyses (e.g., Flato et al., 2013) were performed using only regions covered by observations. However, errors in data may have slightly underestimated recent warming (Karl et al., 2015)

A possible contributor to the different warming rates between most models and observations is errors in forcing: The forcings driving the CMIP5 models do not include the recent solar minimum, which may partly offset recent warming (see e.g. Kaufmann et al., 2011), nor do they include the majority of numerous, small volcanic eruptions of the last decade and thus overestimate net incoming radiation (Santer et al., 2014,2015, Haywood et al., 2013, Neely et al., 2013). In addition, a reduction in methane and chlorofluorocarbons (CFCs) and increase in anthropogenic aerosols (Estrada et al., 2013), along with stratospheric water vapour (Solomon et al., 2010), may also contribute.

Models may also react too strongly to prescribed forcings. Optimal detection and attribution results (Stott et al., 2013, Bindoff et al., 2013) suggest that simulated warming in recent decades in the highest-sensitivity models is too great. However, incorporating the hiatus period into estimates of the transient and equilibrium climate response only reduces the upper limit of the range, with little effect on the lower limit (Johannson et al., 2015).

An important contributor to any model-data mismatch is chaotic fluctuations (internal climate variability), with both models and observations having different realisations of this variability. Model simulations initialised with the observed ocean state match observations better than free-running simulations (Guemas et al., 2013) and Meehl et al (2014) found that the uninitialized CMIP5 simulations that simulated the hiatus (10 ensemble members out of a possible 262) showed a realisation of internal variability very similar to that observed. Periods of reduced surface warming in simulations of historical and future periods tend to show increased storage of heat in the deep ocean (Meehl et al. 2011, Katsman and van Oldenborgh, 2011, Palmer et al., 2011), tentatively supported for the recent period by direct observation (Levitus et al., 2012) and ocean re-analysis (Balmaseda et al., 2013).

The temperature change pattern during decades of reduced warming in model simulations suggests that the Pacific Ocean is a key region (e.g. Meehl et al., 2013,2014, England et al., 2014, Trenberth and Fasullo, 2013, Steinman et al., 2015), with an Interdecadal Pacific Oscillation (IPO) structure and a strengthening of the Pacific trade winds drawing heat down into the deep ocean. Simulations with prescribed sea surface temperatures (SSTs) in the eastern equatorial Pacific reproduce the annual-mean global temperature reasonably well (Kosaka and Xie, 2013). Other studies have found that the Atlantic also plays a role, suggesting that the slowdown is mainly caused by heat transport to the deep layers in the Atlantic and Southern Oceans (Chen and Tung, 2014), and that the Atlantic multi-decadal oscillation (AMO) has contributed to the hiatus (Steinman et al., 2015).

It is likely that the causes of the hiatus lie in a combination of these many different factors, consistent with the conclusion that reduction in global surface temperatures could be “attributable in roughly equal measure to a cooling from internal variability and external forcing” (Flato et al., 2013). When internal variability and the decrease in external forcings are considered, model results are more in line with recent observations (Huber and Knutti; 2012, Schmidt et al., 2014; Marotzke and Forster, 2015).

How likely are hiatus or accelerated warming periods in the future? Meehl et al. (2013) and Maher et al. (2014) found that periods of warming with zero trend are possible in future climate simulations, but are dependent on the scenario followed, with hiatuses very rare in the strongest forced scenarios. Roberts et al. (2015) also evaluate the likelihood of hiatuses and accelerated warming periods of varying lengths due to internal variability in climate model simulations. However, these approaches focus on internal variability in climate models only. Here we estimate the likelihood of hiatus and accelerated warming periods using observations of the last 130 years and a reconstruction of global temperature (Crowley et al., 2014) since 1782. We calculate a separate likelihood of hiatus and accelerated warming periods arising from internal variability and from natural variability, which includes volcanic eruptions and changes in solar radiation. Crowley et al. (2014) concluded that the recent 10-15 years were not unusual in the context of the last 230 years. This study will build on this finding placing it in a more robust quantitative framework.

Data: Observations and Models

During the historical period, we use the GISS Surface Temperature Analysis observational dataset (GISTEMP; 1880-2014; Hansen et al., 2010), which has fairly complete spatial coverage throughout the record. To extend the analysis further back in time, we use a proxy reconstruction of global temperature (Crowley et al., 2014) that covers the interval 1782-1984. The reconstruction is based on a constant number of sites to 1801, with an extension to 1782 after three tropical sites drop out. Each site correlates reasonably well with local temperatures and the reconstruction has good skill in reproducing global temperature, correlating well with the instrumental observed temperatures during the overlapping period (correlation 0.83 for the interval 1907-1984; Crowley et al., 2014). The use of a virtually fixed-grid reconstruction ensures that variance does not change over time due to changing coverage of sites.

The climate response to different forcings is derived from multi-model mean ensembles. For the historical period, many model simulations are available as part of CMIP5. Here we use simulations driven with 1) all external forcings (*ALL*), which combine anthropogenic (greenhouse gases, aerosols, land use and ozone) and natural forcings (volcanic and solar), 2) only anthropogenic forcing (*ANT*), and 3) only natural forcing (*NAT*). Many of the simulations stop in 2005. For the purpose of removing the anthropogenic component, and for the time series plots in fig. 1, we have extended the *ALL* and *ANT* simulations using the rcp4.5 experiments (to 2014 for the *ANT* simulations and to 2050 for the *ALL* simulations). For the same purpose, the *NAT* simulations are extended to 2014 by setting the temperature to the mean of the period 2000-2005. All models are masked to have the same coverage as the GISTEMP dataset. Because the CMIP5 historical period begins in 1850, a multi-model mean of all available all-forced simulations, which is predominately composed of CMIP5/PMIP3 last millennium simulations, is used to extend to 1782. Since no anthropogenically forced simulations exist for this period, we derive an estimate using the CMIP5 anthropogenic simulations starting in 1860 and continuing back in time with well mixed-greenhouse gas forcings scaled to the proxy reconstruction. For model samples of internal variability we use CMIP5 control experiments, excluding those exhibiting an overall trend greater than 0.05K/century (see supplementary tables S1,2 for models used).

Methods

For this analysis, a “hiatus” is assumed to be a period of time with a zero or negative linear trend in global mean annual surface air temperatures. For natural climate variability (whether it be due to external or internal variability) to cause a hiatus in the present or near future, it must have a negative linear trend equal to the projected increase in temperature due to anthropogenic causes. A linear trend of 0.022K/year well approximates the temperature increase in the first half of the 21st century within rcp4.5-extended historical simulations (figure 1a). Thus, a period of internal variability may potentially cause a hiatus only if the linear trend is less than -0.022K/year. Similarly, we also consider periods of natural variability which could cause stronger than expected warming, in particular focusing on samples with linear trends ≥ 0.022K/year, i.e., twice the expected warming. Hereafter these periods will be referred to as ‘hiatus’ periods and ‘accelerated warming periods’, following the convention of Meehl et al. (2013) and Roberts et al. (2015).

Although this paper does not directly analyse the so-called recent “hiatus”, the analysis has been partly motivated by its occurrence. In order to remove any chance of selection-bias we will end our trend analyses in the year 2000.

To calculate estimates of internal climate variability from observations and reconstructions, the externally forced component must first be removed, for which we use climate model simulations. For the historical period (fig 1a), the observations were regressed onto the multi-model mean for a two-signal linear combination of the CMIP5 *ALL* and *NAT* simulations using a total least squares regression (see Allen and Stott, 2003, Schurer et al., 2014, and supplementary text S1, for details of method) with data from the full period (1880-2014), splitting the climate response into anthropogenic and natural components. The result of this analysis is a best estimate and range of scaling factors by which the multi-model fingerprint must be scaled to best match observations. The scaling factors are 0.94 (with a 5-95% uncertainty range of 0.81 - 1.12) and 0.39 (0.16 - 0.66) for anthropogenic and natural forcings, respectively, indicating that the response to natural forcing in the models is stronger than in observations, necessitating scaling to ~40% amplitude. This may be in part due to El Niño events suppressing cooling associated with some of the recent eruptions. Analyses of last millennium reconstructions also suggest that the volcanic signal is smaller than in reconstructions (Schurer et al., 2013; approximately 70% of simulated amplitude), but results are dependent on the reconstruction analysed, and volcanic cooling may be underestimated in the reconstructions since many rely on tree-ring width measurements (see e.g. D’Arrigo et al., 2013). The residual after subtracting the scaled multi-model forced fingerprint, yields an estimate of unforced variability, shown in fig. 1b, where hiatus and accelerated-warming trends of greater than 8 years are highlighted. Note that the residual has been slightly downscaled in order to account for the small amount of internal variability in the multi-model means –see supplement. Similarly, an estimate of internal variability for the longer proxy reconstruction period was calculated from the residual of the scaled all-forced last millennium multi-model mean and the proxy reconstruction (scaling factor 0.66; uncertainty range 0.54 – 0.88), (see fig 1c,d). Samples of model internal variability were taken directly from multi-model control simulations. Results are insensitive to variations in scaling factors for the fit of forced signal to data within their uncertainty (see supplement).

Since hiatus and accelerated warming periods are possible both due to internal variability and natural forcing (solar and volcanic), we also consider the combined effect of both these sources of natural variability (i.e. non-anthropogenic). This effect is estimated by removing the contribution from anthropogenic forcings from the observations. Consequently, the *ANT* simulations are regressed onto the observations (scaling factor, 0.92; uncertainty range 0.80 - 1.10) (see fig. 1a,c) and proxy reconstruction (scaling factor, 0.89; 0.58 – 1.33) (see fig. 1c,d) and then removed. The calculated residual is a sample of observed natural variability. Additionally, model estimates of combined natural variability are taken from *NAT* simulations for 1880-2000. We also use the period 850-1750 from all-forced last millennium simulations, assuming that anthropogenic forcing in this period is negligible. This is likely to be a reasonable assumption since the main anthropogenic effect during this period will be land-use change, which up until this point is likely to have had a small effect in large scale temperatures in model simulations (see e.g. Schurer et al 2014).

Results

Samples of internal variability from models, observations, and the proxy reconstruction contain very similar probabilities of hiatus-causing periods (Fig 2a), with model results similar to that found by Roberts et al. (2015). Short hiatus periods of a few years are relatively common with the probability decreasing to approximately 20% for 5-year periods (24% In models, 23% in observations and 19% in proxy reconstruction), approximately 5% for 10-year periods (5%, 6% and 5%) and close to zero for 15-year periods (0.4% in models). This means that in the near-future, due to internal variability alone, short periods of time without any increases in temperature are likely to be quite common, while hiatus periods of over 10 years should be less likely. A similar picture is seen for accelerated warming periods; frequent short periods which could cause double the expected warming (fig 2d) are common, but there are very few periods in excess of 10 years. Our results are insensitive to scaling factors within the 5-95% range when subtracting the forced component (see supplementary fig S10).

The spatial patterns associated with these trends are shown in fig. 3. Here we consider just the 8-year trends, which is a compromise between analysing longer periods of unusual internal variability and sample size. This results in 13 observed hiatus samples (of which 4 are non-overlapping) and for 10 accelerated warming samples (of which 4 are non-overlapping). Results for periods up to 12 years are broadly similar.

The spatial trends during hiatus periods in observations (fig. 3a) show a clear IPO pattern with a significant cooling over the tropical Pacific and parts of the high latitude Northern and Southern Pacific, and warm anomalies in the northwest and southwest Pacific. The pattern is similar to that from model control simulations (fig 3b) and these are in turn similar to those previously calculated by Roberts et al. (2015) and Maher et al. (2014). This suggests that models correctly simulate both the frequency and the dominant spatial pattern of observed hiatus events. The most recent hiatus also exhibits a similar pattern (see e.g. Meehl et al 2013, Kosaka and Xie 2013), suggesting it is not unusual in the context of the past several hundred years. In addition to the IPO pattern, observations show more spatial variability than in models, with significant cooling in the Atlantic and Indian oceans, but with some warming in Northern Europe. This pattern originates to a substantial fraction from the boreal cold season (November-April) (fig. 3e) in both models and observations, while the boreal warm season (May-October) pattern is similar but muted (see supplementary information, fig S5). The stronger boreal winter pattern agrees with observations of the recent hiatus (e.g. Cohen et al 2012, Kosaka and Xie 2013).

The accelerated-warming patterns are almost the exact opposite to the hiatus patterns, with significant warming in the tropical Pacific in both observations (fig 3c) and models (fig 3d), and also with stronger warming in the boreal cold-season (see supplement). Similar to the hiatus patterns, the observations also show significant trends in the Indian Ocean and Atlantic as well as a prominent warming in Asia and cooling in Europe. Examples of such warming occurred in the 1990s (fig. 1).

Since previous analyses of hiatus decades (Meehl et al., 2013, Steinman et al., 2015) focussed on the role played by the North Atlantic and tropical Pacific, we analyse the trends of the mean temperatures only over these two areas (Supplementary fig S4; note that limited data coverage precludes long-term analysis of the Southern Ocean). This illustrates that large long trends in global mean temperature are nearly always accompanied by trends in the Pacific cold tongue in both models (~95% significance) and observations, both of which are stronger than the global mean trend. On the contrary, in models, large long trends in global mean are not necessarily associated with trends in the North Atlantic. Observation results in the Atlantic are mixed, with the observed warming periods following the models while hiatus periods seem associated with larger cooling. This observation-model discrepancy in the North Atlantic is significant for hiatus periods of 9 to 10 years, but the interpretation of this result is difficult due to small sample size.

We turn now to trends caused by all natural variability, both forced and internal. Fig. 2c shows the probability of finding hiatus-causing periods of varying length in our samples of combined natural variability covering the observational period, while fig. 2e shows the same but for the periods of accelerated warming. The samples estimated from observations show only a slight increase in likelihoods, particularly for longer periods, to that estimated for just internal variability (compare the red dots to the black line and to fig 2a,d). This means that during the historical era, natural forcings (solar and volcanic) do not seem to have contributed much to decadal trends. This is not the case in models however, where the inclusion of natural forcings over the same period (green dots) see a large increase in trends, with hiatus-causing trends and accelerated warming trends of 15 and even 20 years now possible. This discrepancy is because, as already noted, models show stronger responses to natural forcings than seen in observations (see scaling factors calculated for natural forcings – method section). This is particularly noticeable for the Krakatau eruption in 1883, which has a large impact in models, but is much smaller in observations (see Fig. 1a,c). This discrepancy could be due to forcing uncertainty, observational coverage or errors in the modelled response (see e.g. Joshi and Jones 2009 and Hansen et al., 2009).

The results for natural variability from the proxy reconstruction however show an increase in both the hiatus and accelerated warming trends (figs 2c,f) compared to that estimated for just internal variability over the same period (figs 2a,d). This is because the proxy reconstruction contains one of the strongest volcanic eruptions in recent history, Mount Tambora in 1815, which occurred during a period of high volcanic activity generally as well as a the Dalton solar minimum. This resulted in a large cooling signal seen in both models and observations (fig 1c). A long term cooling followed by a temperature recovery is prominent in the residuals (fig 1d), which if it occurred now could cause a hiatus lasting over 20 years followed by a period of accelerated warming of another 20 years. Model simulations of pre-industrial climate (850-1750) also show large trends with hiatus-causing trends of greater than 25 years possible.

To assess the role of volcanic eruptions as pacemakers for hiatus and accelerated warming events, we calculated the likely timing of volcanic eruptions within hiatus periods in observations, reconstructions and model simulations (fig. 4). Figure 4 compares the frequency of occurrence of volcanic eruptions per year within hiatus/accelerated warming events with the average occurrence rate over the last millennium. Many hiatus period have a higher occurrence rate of volcanic eruptions towards their end (orange/red shading in fig 4a,b,c,d) compared to the average occurrence rate over the data period (5/121 years for the observation period, 9/203 for the reconstruction period and 17/901 for the period 850-1750). Nearly all very long hiatus periods have a volcanic eruption during their second half (75% of periods over 16 years in length, see supplementary Fig S5). Long hiatus periods are also much less likely to have a volcanic eruption just before the start of the event (blue shading fig. 4a,b,c,d). For accelerated warming episodes (fig 4e,f,g,h), an eruption is most likely to have occurred just before or at the start of the period, with the warming caused by the recovery (occurring in over 50% of very long warming periods, Fig s5). Indeed, in the reconstructions all the accelerated warming episodes longer than 13 years are associated with the Tambora volcanic eruption. In addition, long accelerated warming periods are clearly associated with a reduced chance of volcanic eruptions during the subsequent portion of the period (see fig 4e,f,g,h and S5).

Discussion and conclusions

By analysing a proxy reconstruction, observations, and models results, we have shown that the recent 'hiatus' is not unusual in the context of past variability, a conclusion which is supported by many previous studies (e.g., Easterling and Wehner, 2009, Meehl et al., 2013, Maher et al., Crowley et al., 2014, Roberts et al., 2015). Here, we go beyond these previous studies by comparing the probability and pattern of hiatus and accelerated warming periods between observations and climate models. We consider separately the two most important sources of decadal variability: natural external forcings (solar and volcanoes) and internal variability, within both models and observations, in one self-consistent analysis. We have also made use of a recently published temperature reconstruction (Crowley et al., 2014), to extend our analysis back further, to 1784.

Our findings show that the likelihood of hiatus and accelerated warming periods in observed internal variability is very similar to that calculated previously for models (Roberts et al., 2015) and that the spatial fingerprint of each are similar, displaying a clear IPO pattern. We also intriguingly find suggestive evidence that there is a larger Atlantic signal in the observed hiatuses (supporting Steinmann et al., 2015 who also found a role for the AMO in observations) and find a stronger signal in the Indian Ocean and Asia and a signal of opposite sign in Northern Europe. Due to the limited sample size for observed hiatuses, this result should be taken with caution, although the Northern European pattern is tentatively supported by the proxy reconstruction (see supplement, Fig S8).

While Maher et al (2014) noted that the likelihood of hiatuses in model simulations increases for decades containing volcanic eruptions, in both models and for three out of four of the largest volcanoes in observations, their analysed time series contained anthropogenic forcing. Here we overcome this by first removing the anthropogenic forcing from the observations and by using the CMIP5 models driven only by natural forcings, which allow these results to be directly compared to those for internal variability alone.

We find that in models, the presence of natural forcing in the period 1880-2000 greatly increases the chances of hiatuses and accelerated warming periods. These likelihoods are increased further if we instead consider the period 850-1750, with the majority of the long hiatuses being caused by large cooling due to a volcanic eruption towards the end of the hiatus period, while the accelerated warming periods generally represent a recovery from the volcanic cooling. The sample of natural variability extracted from the temperature proxy reconstruction also shows much greater likelihood of hiatuses and accelerated warming periods, predominately due to the presence of a period of high volcanism at the start of the 19th century, which includes the Mount Tambora eruption in 1815. Natural variability samples from observations (1880-2000), however, show only slight increases in the likelihood of both hiatuses and accelerated warming. Some of this may be due to an overestimate of at least some volcanic events in climate models, a problem that may also occur over the last millennium. However, the recent period has seen comparatively weaker volcanic activity than some periods of the last millennium, particularly the early 19th century, 13th century and mid-15th century and a hiatus lasting several decades could be possible if one or several sufficiently large volcanic eruptions were to occur.

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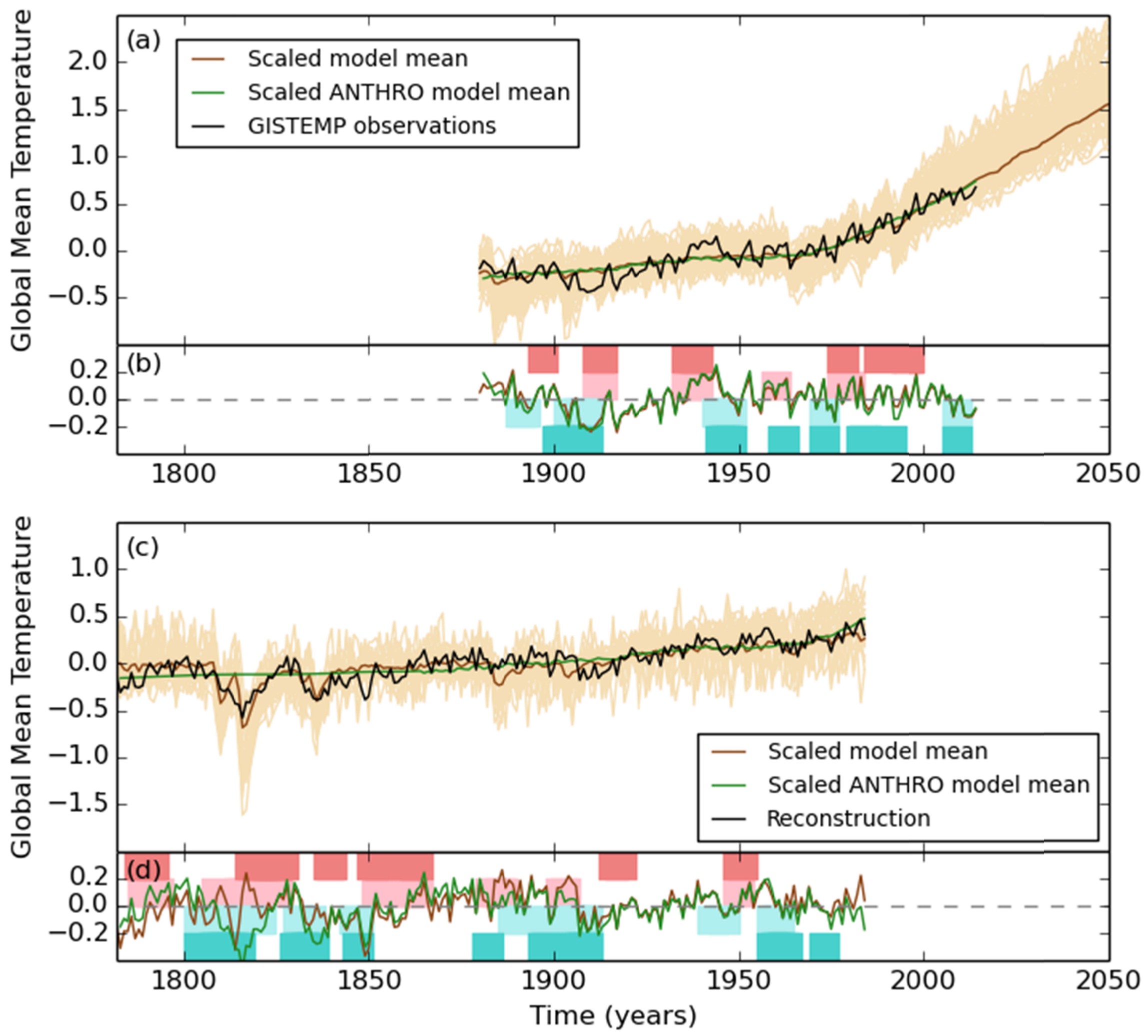

Fig. 1 – *Global annual mean surface temperature for models and observations* –observations (a) and a proxy reconstruction (b) are compared with a combination of models accounting for all forcings (brown) and just anthropogenic forcing (green). In both the multi-model mean is regressed onto the observations. In figure a) the multi-model mean is extended using the projected rcp 4.5 scenario. Panels b) and d) show the difference between observations/reconstruction and models (brown: after removing all forcing; green after removing anthropogenic forcing only). Hiatus causing trends of longer than 8 years are shown in blue, accelerated warming trends in red; lighter shade for those caused by internal variability only and darker shade for those caused by all natural variability (see method section for details).

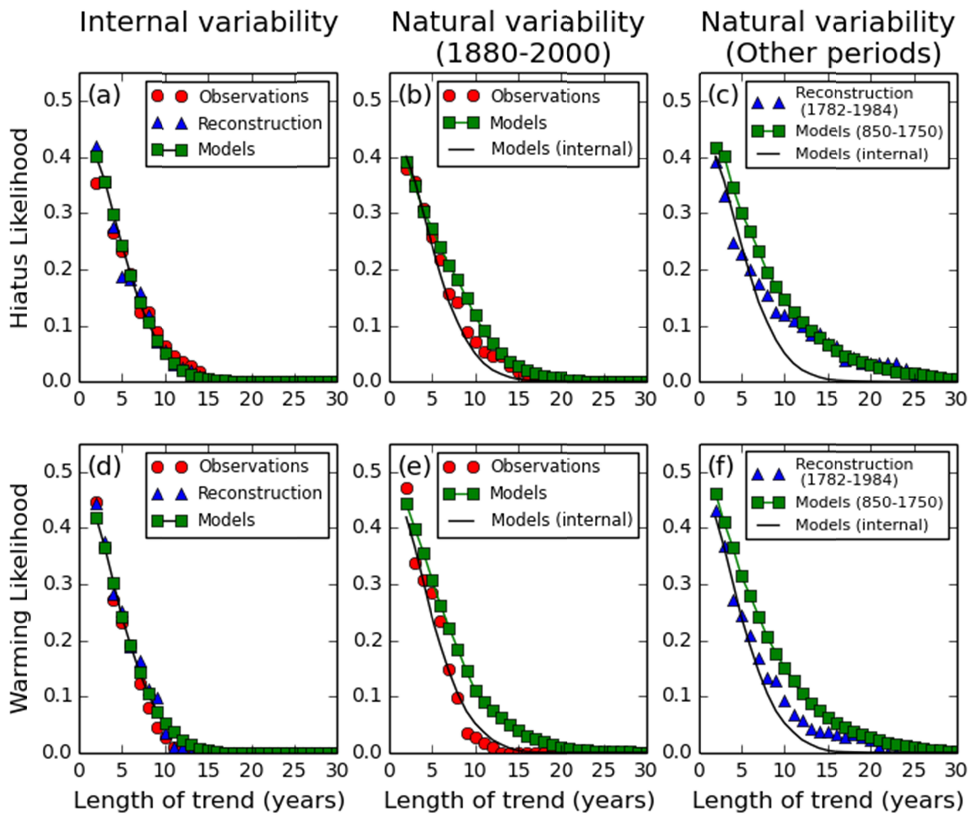

Fig. 2– *Probability of occurrences of hiatus and accelerated warming events*– a) and d): Events due to internal variability only, selected where trends in internal variability are a) large enough to counter predicted warming for the 21st century or d) cause two times the predicted warming. Model results come from CMIP5 control simulations. b) and e): Events due to internal variability and natural forcing combined (1880-2000). Model results come from CMIP5 *NAT* simulations. e) and f) Events due to internal variability and natural forcing. Model results for 850-1750 come from PMIP last millennium simulations (assuming for simplicity that all forcing during this period is natural). Results for control simulations with just internal variability (fig 2a&d) are shown in all panels (black line) for a comparison.

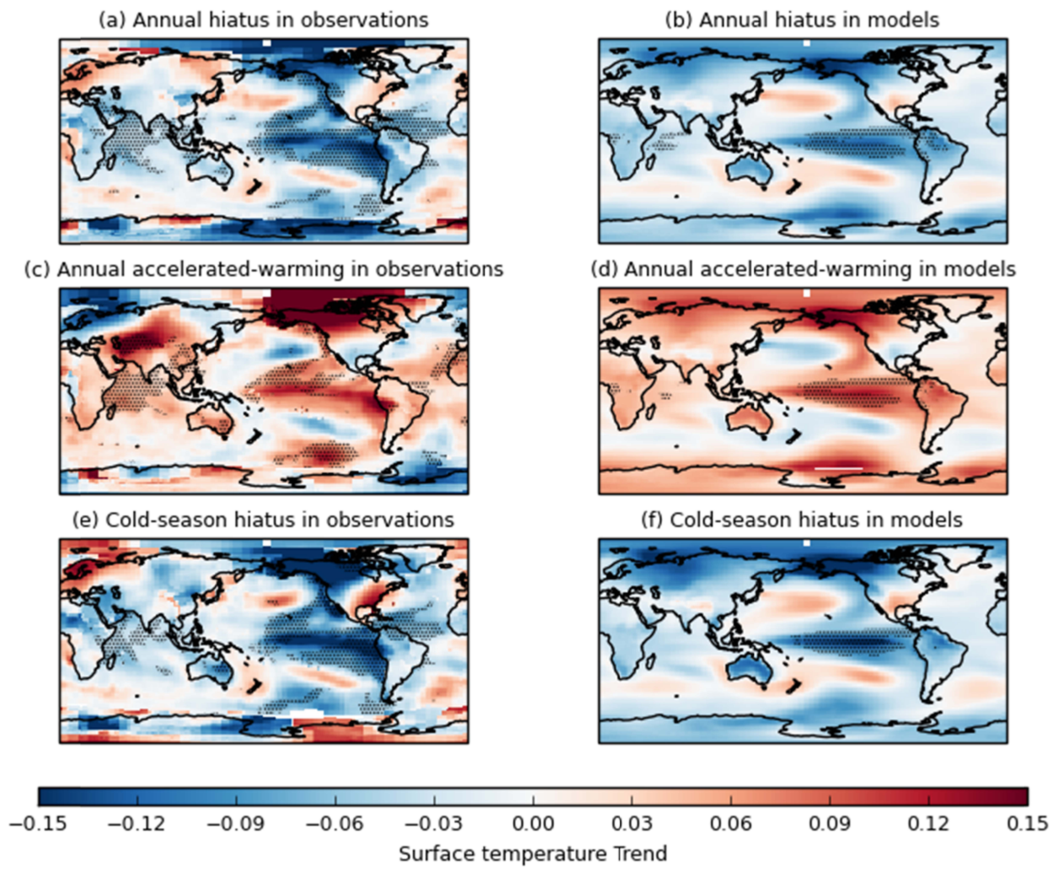

Fig. 3 – *Spatial patterns of unusual periods of internal variability* – Mean annual 8-year spatial trends for samples of internal variability taken from: a)&c) the observational residual b)&d) the model control simulations. Periods in a)&b) are selected so that global trends are large enough to counter-act projected warming. Periods in c)&d) are selected so that global trends are large enough to cause two times the predicted warming. Stippling indicates 80% agreement in sign of trend between all selected samples. e) and f) show hiatus periods in the boreal cold season. Results for the accelerated warming in the boreal cold season are similar but of opposite sign, hiatus and accelerated warming events in the boreal warm season show a weaker signal (see supplement, fig. S5).

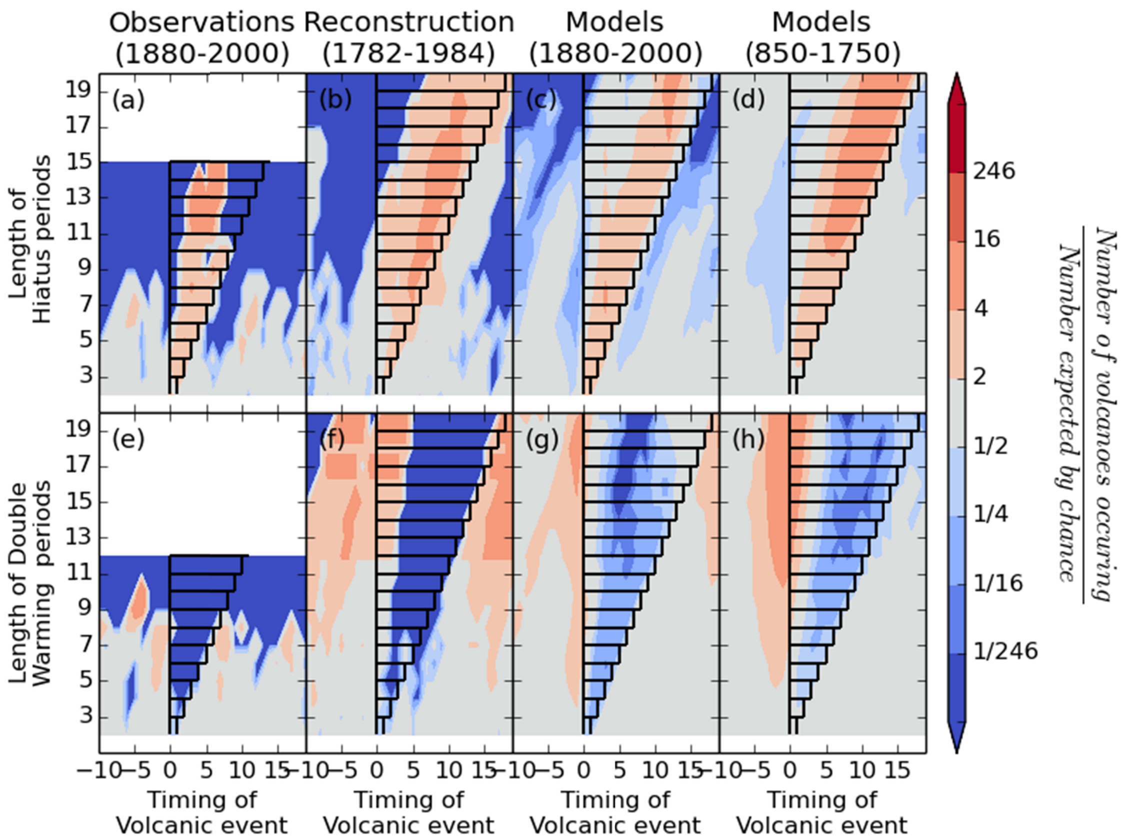

Fig 4 – *The role of volcanic eruptions in hiatus and accelerated warming periods*. Each panel is based on a series of epoch analyses, averaging across hiatus/accelerated warming events of specified length (vertical axis). The horizontal black box, beginning at 0, indicates the extent of the event. The colour shading indicates the number of volcanic eruptions occurring in a particular year of a hiatus/accelerated warming event divided by the average occurrence rate taken over the whole analysis period (blue shading indicating below average occurrence of eruptions, orange/red above average).